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EFFECT OF INTERACTING VORTICES ON JET PENETRATION INTO A SUPERSONIC STREAM

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16. Abstract

Helium, at sonic velocities, was injected into the interaction region of a counter-rotating vortex pair, a single vortex, and a vortex-free flow field in a Mach 2 free stream. The vortex pair and the single vortex were generated by injectors having double and single swept edges, respectively, at a 6° angle of attack. Penetration at 12 jet diameters downstream from the injection orifice was 11 to 18 percent greater for the double-tip injector than for the single-tip injector. Injection pressure was varied from 60 to 100 psia (4.15×10^5 to 6.89×10^5 N/m^2). Total free-stream pressure was 0.92 atmospheres (9.3×10^4 N/m^2).

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SUMMARY

Penetration was measured for helium injection into the interaction region of two converging counter-rotating vortices in a Mach 2 airstream. Results were compared with injection into single vortex and vortex free flow fields. The counter-rotating vortices were generated by an injector having two delta shaped tips with opposing sharp sweptback leading edges. The single vortex was generated by a single tip delta shaped injector with one sharp sweptback leading edge. The injector for the vortex free flow field was a flat wedge shaped plate with a sharp unswept leading edge. The injectors were all mounted at a 6° angle of attack to the free stream. Injection pressure was varied from 60 to 100 psia (4.14×10^5 to 6.89×10^5 N/m^2) at sonic velocity. The measurements were made in a 25.4 by 9.75 centimeter wind tunnel.

Penetration at 12 jet diameters downstream from the injection orifice was 11 to 18 percent greater for the double tip injector than for the single tip injector. Concentration and pitot tube pressure surveys indicated that the jet and counter-rotating vortices lost their separate identities and combined into a single flow system. In contrast, the jet did not combine with the vortex of the single tip injector, but instead disrupted and displaced it.

INTRODUCTION

Penetration of fuel injected from a wall into a supersonic stream remains a critical problem in the development of the supersonic combustor (ref. 1). This is because the injectant, for the case of an underexpanded jet, quickly loses its momentum through a normal shock (Mach-disk) and is subsequently turned nearly parallel to the free-stream flow. The result is poor fuel-air distribution within the combustor. Numerous studies (refs. 2 to 9) have investigated wall injection parameters which control jet penetration into a supersonic stream. Results have shown that adjustment of these parameters to maximize jet penetration have relatively small effects. Struts, which are carefully designed to minimize aerodynamic heating and drag losses, may solve the problem of fuel injection in supersonic streams.

It was suggested by Townend (ref. 10) that injectors for supersonic combustion be designed to shed vortices. Fuel, if injected from appropriate locations, would be entrained by the vortices and penetrate further into the free stream than it would if the vortices were absent. The vortices are generated by swept wedges or delta wings at angle of attack. Experimental studies of injection into a supersonic stream from delta wings at angle of attack are reported in references 11 and 12. These studies considered only a single vortex.

Two reasons exist for studying the effects of interacting vortices on jet penetration into a supersonic stream. First, a practical injection system of course would involve numerous vortices which may interact. Second, Maltby and Peckham (ref. 13) show that counter-rotating vortices elongate in a direction normal to the delta wing surface. This phenomenon might then be used to further enhance jet penetration into a supersonic stream.

The counter-rotating vortices of Maltby and Peckham (ref. 13) are generated by the leading edges of a highly sweptback delta wing. These vortices, however, diverge with increasing downstream distance. The interaction effect might be increased if the counter-rotating vortices converge rather than diverge. The purpose then of the present study is to determine experimentally the effects of convergent counter-rotating vortices on jet penetration into a supersonic stream.

The counter-rotating vortices were generated by a double-tip injector having two opposing sharp sweptback leading edges, which joined to form a sharp crotch on the surface of a flat plate. The injection orifice was located on the leeward surface of the plate near the convergence of the vortices. Penetration produced by this injector was compared with that obtained by injection from a single-tip delta of the same sweepback angle and with that by injection into a flow field in which vortex motion was absent. This was accomplished by injection from a flat plate having a sharp unswept leading edge. All three injectors were at a 6° angle of attack to the free stream.

The injectant was helium at sonic velocity. Injection pressure was varied from 60 (4.14×10^{5} N/m^{2}) to 100 psia (4.14×10^{5} to 6.89×10^{5} N/m^{2}). The free-stream Mach number was 2 at a stagnation pressure and temperature of 0.92 atmosphere (9.3×10^{4} N/m^{2}) and 347 K, respectively.

SYMBOLS

d injection orifice diameter

M Mach number

P pressure

v velocity

x distance from injection orifice, parallel to free stream

y vertical distance from injector surface, normal to free stream

z lateral distance from injection orifice

γ specific heat ratio

ρ density

Subscripts:

dt refers to double-tip injector

st refers to single-tip injector

APPARATUS AND PROCEDURE

Injectors

Planform, side, and cross sectional views of the injectors are shown in figure 1. The leading edges of the vortex generating injectors (figs. 1(a) and (b)), have a sweepback angle of 67.5°. Therefore, the free-stream velocity component normal to the swept edges was subsonic. The wedge angles of the swept edges were 32.6° and 60° for the double- and single-tip injectors, respectively, as shown in figure 1.

The injection pressure reported here was measured in the helium flow line outside of the tunnel. A calibration indicated that the total pressure loss downstream from the measurement point to the injector orifice was approximately 15 percent of the measured pressure.

Concentration Measurements

Penetration and spreading of the helium jet into the Mach 2 airstream was determined from concentration measurements of gas sampled downstream of the injection

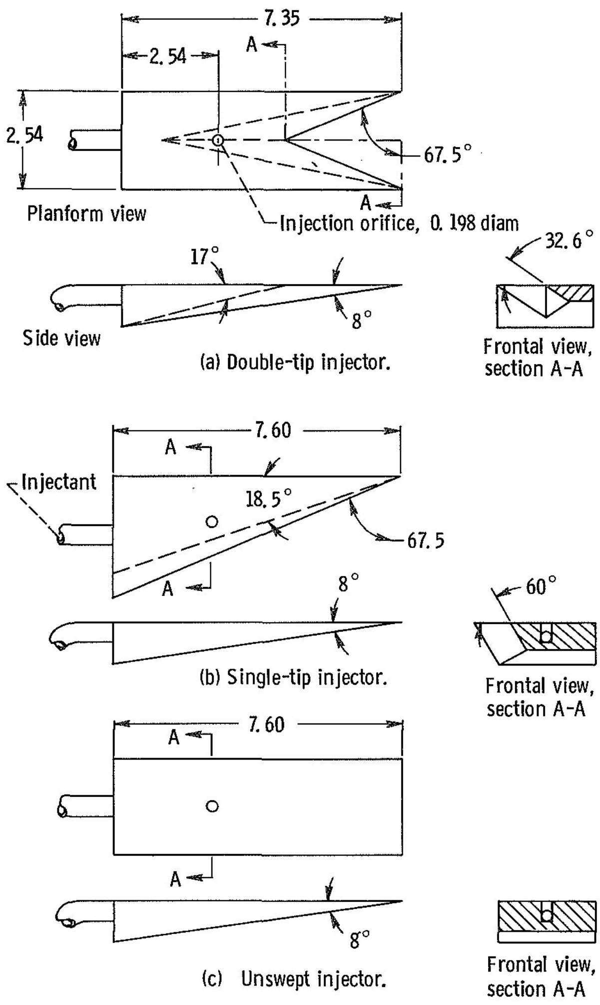


Figure 1. - Injectors (dimensions in cm).

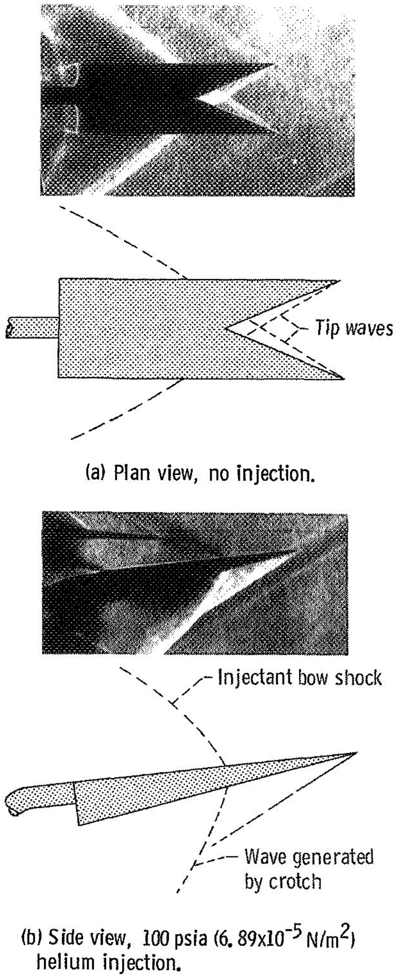


Figure 2. - Plan and side-view Schlieren photographs of double-tip injector (tunnel flow left to right).

point. The gas sampling, analysis technique, and probe configuration are described in reference 11. All measurements were made in a 25.4 by 9.75 centimeter wind tunnel, which was described in detail in reference 11.

Schlieren Observations

Plan and side-view Schlieren photographs of the double-tip injector (fig. 2) show shock waves which radiate from the tips and crotch into the windward flow field. The tip waves intersect with each other and with the wave generated by the crotch. The curvature of these waves may be attributed to the windward injector surfaces and the wave intersections. Extrapolation of the wave in the crotch to the leeward surface indicates that it originates at the crotch. However, the exact point of origin, being hidden by the injector, cannot be determined. It is estimated though, that the distance by which the wave may be detached at the crotch is on the order of the Schlieren system resolution. If detachment does exist, then flow might circulate from the windward region and spill over at the crotch into the leeward flow stream. It would be expected that spillage over the crotch into the leeward flow field would generate a visible shock. Examination of the side-view Schlieren photograph (fig. 2(b)) shows a weak expansion fan in this region. This disturbance is much weaker than the interaction shock caused by the jet. It is therefore assumed that the effect of spillage, if any, on the leeward flow field is small. The other waves in the photographs originate from the probe, injector trailing edges, sting support, and minor discontinuities of the tunnel walls.

Concentration measurements were obtained at several downstream stations. Lateral surveys at each station were obtained by rotating the probe at an angle of yaw. Thus, the probe tip at each downstream station described a cylindrical surface. However, the curved sampling surface approximated a plane to within 0.5 injection orifice diameters for a probe swing of ±4 jet diameters from a line directly downstream of the injection orifice.

Pressure Measurements

Pitot and static pressures were measured in the flow stream over the injector surfaces. The pitot pressures were measured using the concentration probes. The static pressure probe was made of 1.01-millimeter-diameter tubing with a conical tip. Four 0.34-millimeter-diameter static-pressure holes were equally spaced about the circumference and were located 12 tube diameters downstream from the probe tip.

RESULTS AND DISCUSSION

Concentration Measurements

A typical helium concentration profile is shown in figure 3. Concentration contours (figs. 4 to 6) were constructed from sets of profiles at several downstream stations. The contours are shown as they would appear to an observer viewing the flow field over the injector surface from an upstream position.

Contours for the double-tip injector (fig. 4) suggest that the jet began to separate from the plate surface at $x/d = 5.12$. At $x/d = 13$, the injectant appears to be completely separated from the plate surface. The contours are approximately symmetrical about the injector centerline.

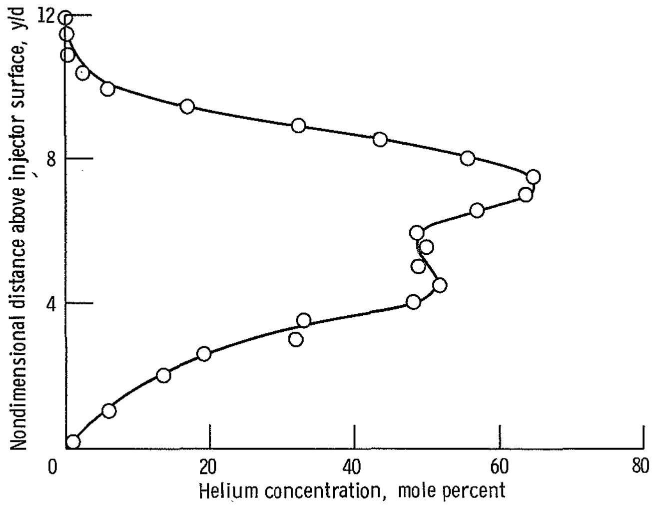


Figure 3. - Typical concentration profile: double-tip injector; nondimensional lateral distance from injection orifice, -1 jet diameter; injection pressure (measured at plenum), 100 psia (6.89×10^5 N/m^2); nondimensional downstream distance, 13 jet diameters.

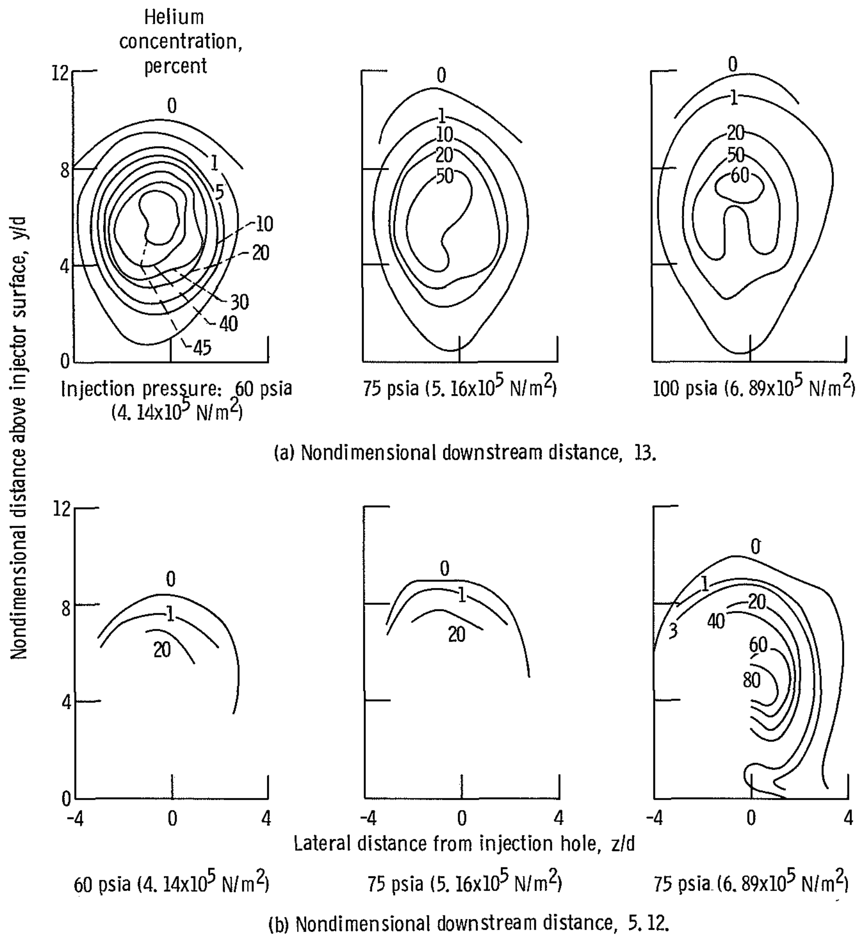


Figure 4. - Concentration contours across flow field; double-tip injector.

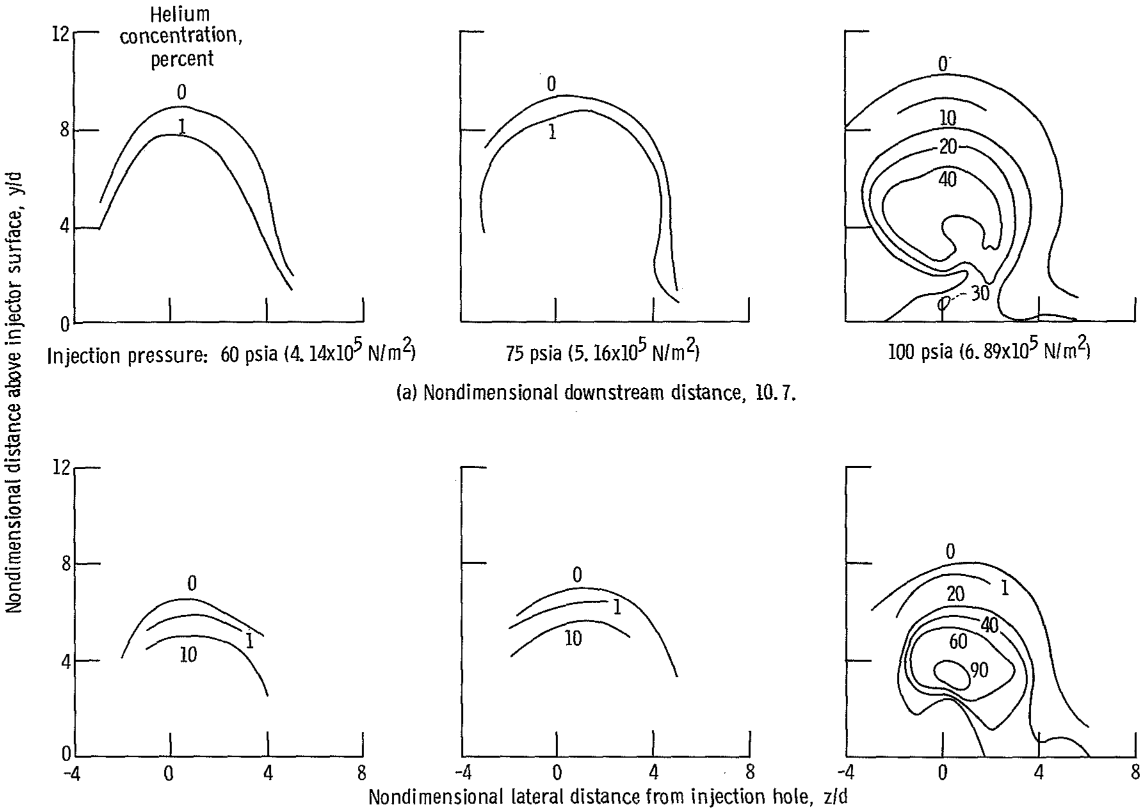


Figure 5. - Concentration contours across flow field; single-tip injector.

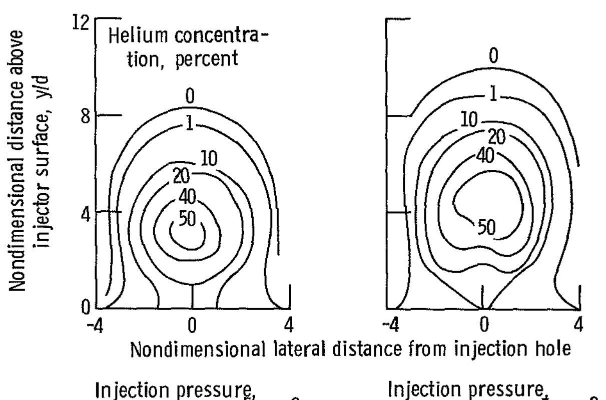
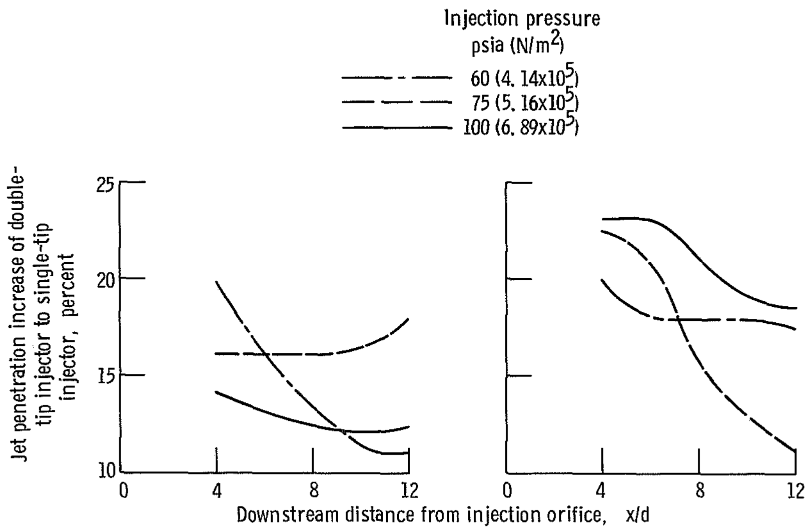


Figure 6. - Concentration contours across flow field; flat plate nondimensional downstream distance, 15.8.

The contours for the single-tip injector (fig. 5) indicate that helium remains attached to the injector surface. These contour patterns, in contrast to those for the double-tip injector, are asymmetrical, and are skewed towards the sweptback leading edge. The shapes of these contours are similar to those for the delta wing at 6° angle of attack in reference 12.

Concentration contours for the unswept injector are shown in figure 6. These contours show the helium distribution in a vortex free-flow field, when injected from a flat plate at an angle of attack. These contours are symmetrical about the injector centerline. The injectant remains attached to the plate at nearly 16 jet diameters downstream from the orifice. Tip vortices, generated by the unswept injector at an angle of attack, were not detected in this study, but may have existed outside the field of measurement.

A comparison of penetration for the swept injectors is shown in figure 7. The percent increase of penetration for the double-tip injector relative to the single-tip injector is shown as a function of downstream distance x/d. The penetration gain varies somewhat randomly as a function of injection pressure, downstream distance, and whether the 0 or 1 percent concentration boundaries are considered. It is therefore difficult to characterize the penetration increase by a single number. The smallest penetration increase is approximately 11 percent for the zero-percent concentration boundary at an x/d = 12. The greatest penetration increase is 23 percent for the 1-percent concentration boundary near the injection orifice. The downstream penetration, however, is of greatest interest. At x/d = 12, the penetration increase due to the interacting vortex effect varies from about 11 to 18 percent.



(a) Penetration of zero-percent helium concentration boundary.

(b) Penetration of 1-percent helium concentration boundary.

Figure 7. - Penetration comparison of double-with single-tip injector.

In making this comparison it must be remembered that the vortex is generated only along the sweptback edge. The sweptback portion, and thus the vortex generating length of the double-tip injector, is only about one-third that of the single-tip injector. Furthermore, the injection orifice of the double-tip injector is located in a region of vortex decay; the orifice of the single-tip injector is in a region of vortex generation. It is thus reasonable to attribute the increased penetration observed with the double-tip injector to interacting vortex effects.

These results suggest that equal or better penetration might be achieved with double-tip vortex generator of shorter length than a single-tip injector.

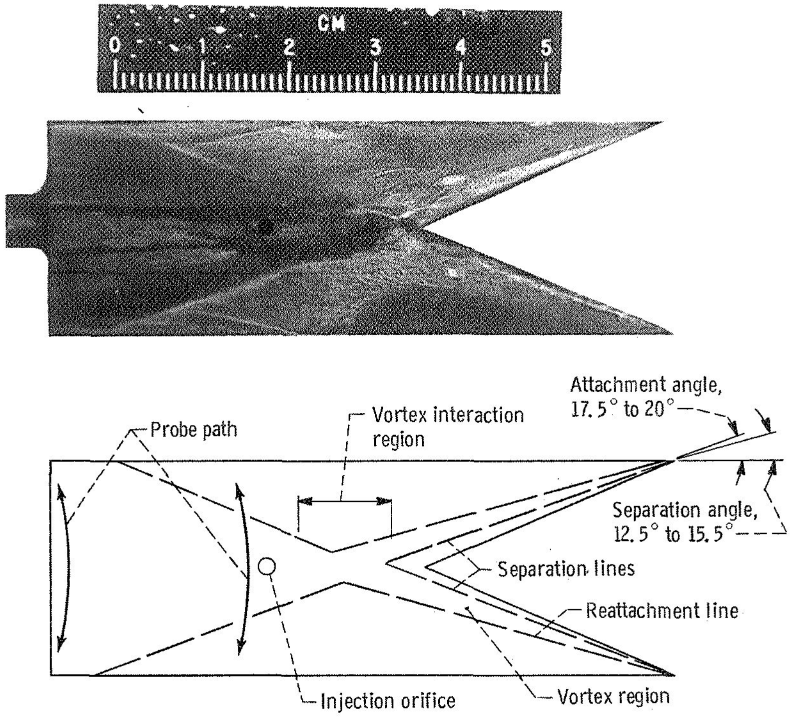
Surface Oil Streak Patterns

The flow over the swept injectors was visualized by surface oil flow patterns (figs. 8 and 9). Because long periods were needed to establish well defined flow patterns, the injectant was air rather than helium. The flow patterns, photographed after the injectors were removed from the tunnel, are partly obscured by transient oil flows which occurred during the flow shutdown. The important surface flow features observed during steady-state conditions are shown in the accompanying sketches. Also shown is the projection of the path of the probe tip on the injector surface for the concentration measurements.

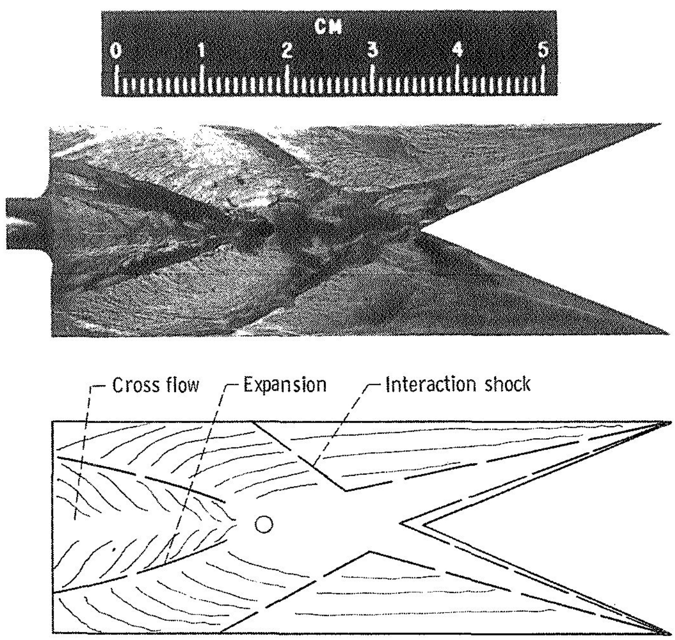
The pattern for the double-tip injector with no injection (fig. 8(a)), shows the extent of the vortex interaction region on the injector surface. With injection (fig. 8(b)), the interaction region became somewhat broader in the z direction and moved slightly upstream.

The oil streak pattern for the single-tip injector resembles that of reference 11. The vortex pattern with no injection is clearly defined (fig. 9(a)). The pattern indicates that the mean position of the vortex was near the injection orifice. Disruption of the vortex flow by injection is indicated by the patterns of figure 9(b).

The positions of the vortex separation and attachment lines obtained from the oil flow patterns are shown in figure 10. Also shown are the calculated separation and attachment line positions of Pershing (ref. 14) and the experimental positions of Povinelli, Povinelli, and Hersch (ref. 12). The positions of the separation lines of the present study agree rather well with previous data. The positions of the attachment lines, however, differ somewhat from the previous experimental results.

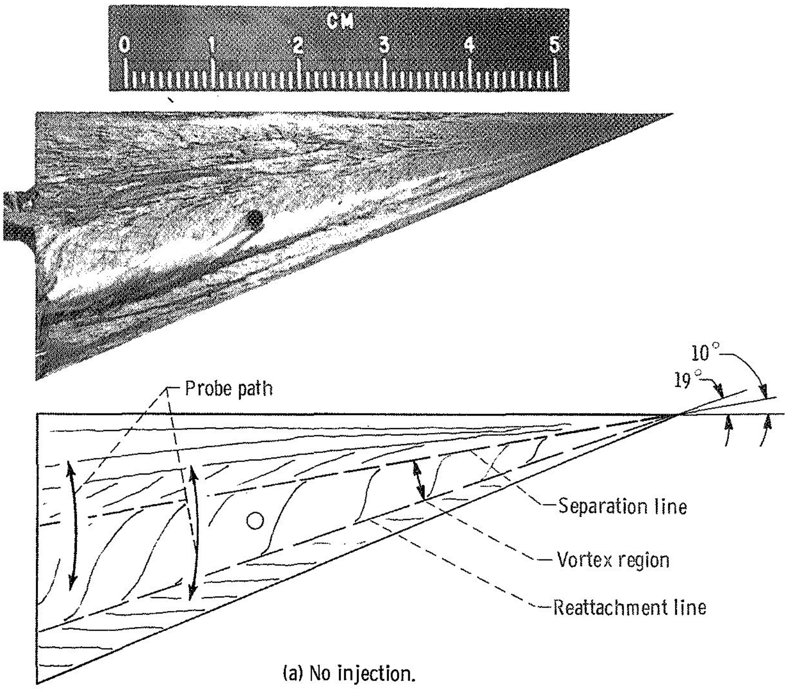


(a) No injection.

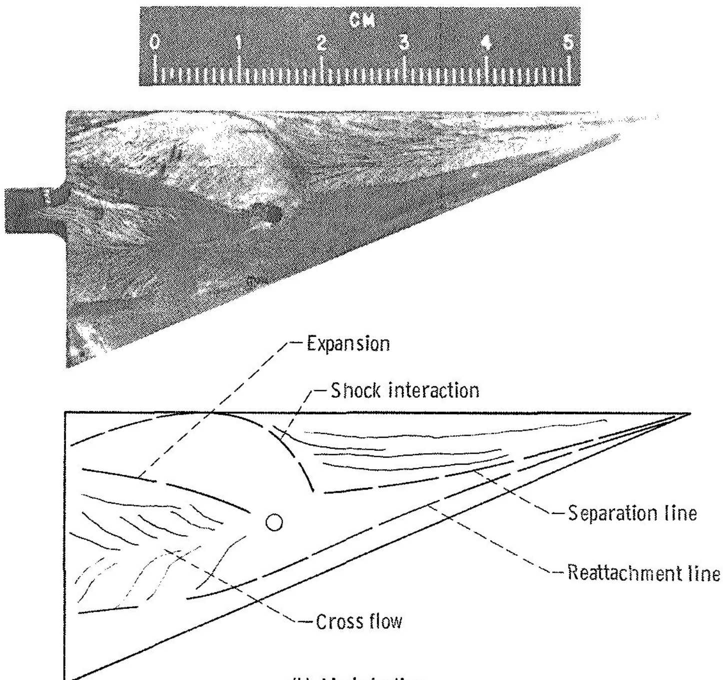


(b) Air injection.

Figure 8. - Surface oil streak patterns on double-tip injector.



(a) No injection.



(b) Air injection.

Figure 9. - Surface oil streak patterns on single-tip injector.

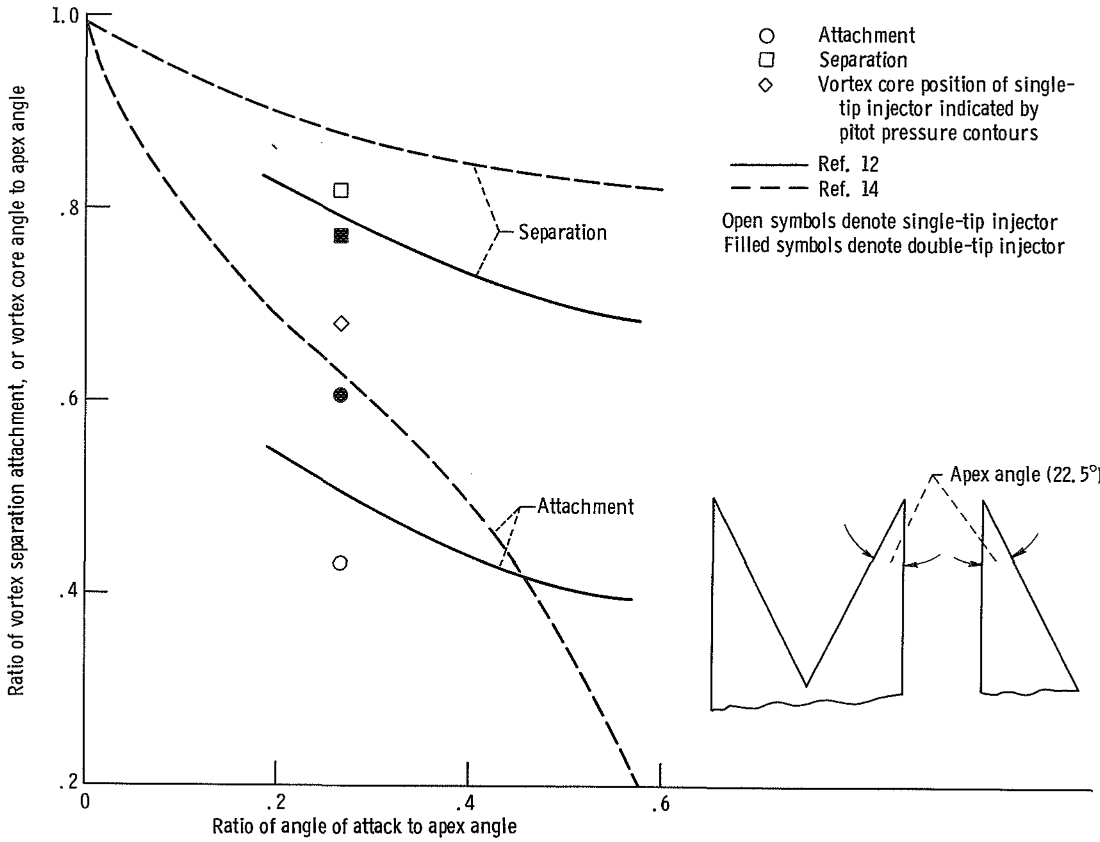


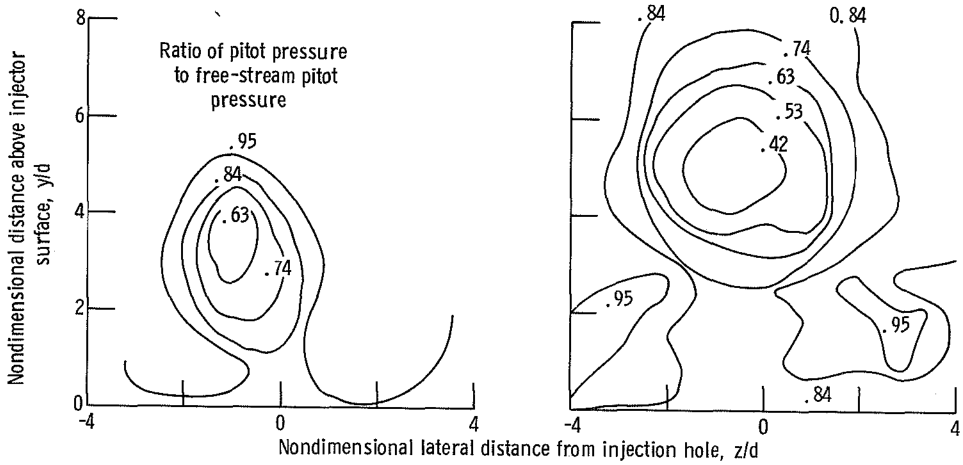
Figure 10. - Comparison of separation and attachment angles to previous results.

Interaction of Jet and Vortex

The interaction of the jet with the vortex was investigated by pitot pressure surveys over each of the three injectors with and without injection. For this purpose, the injectant was air at a pressure of 100 psia (6.89×10^5 N/m^2).

Vortex flow patterns over the surfaces of the swept injectors with no injection are indicated by the pitot pressure contours of figures 11(a) and 12(a). Effects of injection on the flow over these injectors is indicated by the contours of figures 11(b) and 12(b). The flow patterns over the unswept vortex free injector without injection are indicated by the contours of figure 12(a). The contours of figure 12(b) indicate the jet position in the absence of a vortex.

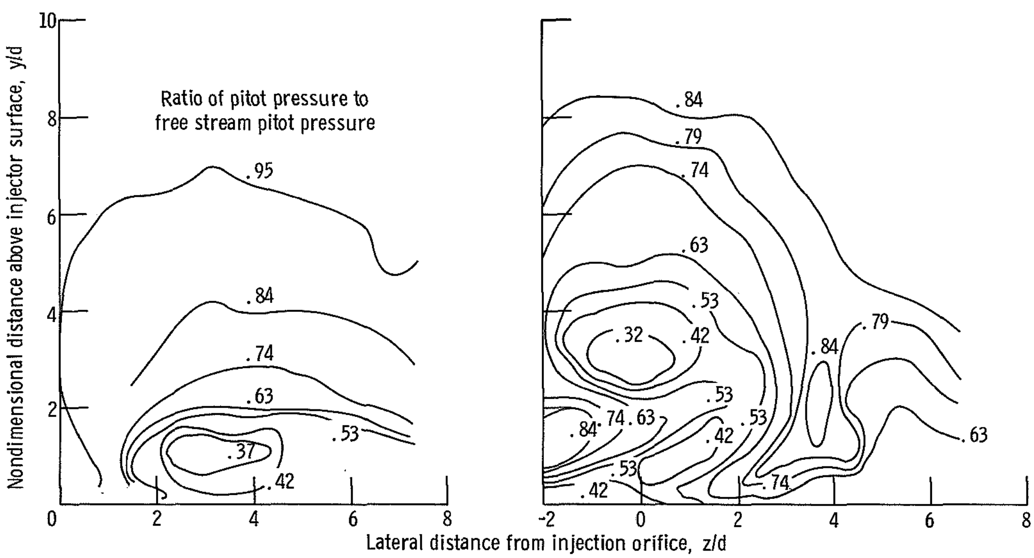
The contours of figure 11(a) suggest that the individual vortices generated by the double-tip injector have coalesced into a single system at $x/d = 13$, forming a symmetrical low-pressure region, which suggests a single vortex core. The flow phenomena that gives rise to this vortex motion is unknown. It might be expected that two vortex patterns would be present side-by-side, downstream of the interaction region. How-



(a) No injection.

(b) Air injection; injection pressure, 100 psia (6.89×10^5 N/m^2).

Figure 11. - Pitot pressure contour lines above double-tip injector. Nondimensional downstream distance, 13. Viewed from downstream direction.



(a) No injection.

(b) 100 psia (6.89×10^5 N/m^2) air injection.

Figure 12. - Pitot pressure contour lines above single-tip injector. Nondimensional downstream distance, 11.4. Viewed from downstream direction.

ever, the pressure survey used to obtain the contours of figure 11(a) covered the area bounded by $y/d = 0$ to 12, and $z/d = -4$ to 4, and only a single low-pressure area was detected. The system is approximately symmetrical, and is located near the injector centerline at about 3.5 orifice diameters above the surface. The lateral z/d position agrees with the surface oil flow patterns. With injection (fig. 11(b)) the vortex and jet appear to have completely combined into a single system. Evidence of cross flow motion on the plate surface with injection is indicated by the oil flow patterns.

Pitot pressure contours above the single-tip injector with no injection (fig. 12) indicate a vortex core at $z/d \simeq 3$ and $y/d = 1$. The lateral position agrees with the oil streak flow lines. With injection (fig. 12(b)) the contours are very complex, showing several concentric ring patterns. The largest is centered directly downstream of the injection orifice at $z/d = 0$ and $y/d = 3$. This, by comparison with the helium concentration contours of figure 5, evidently indicates the jet position. It must be remembered, of course, that the molecular weight and specific heat ratio of air differ from that of helium, which might contribute to some of the differences between the pressure and concentration contour patterns.

A low pressure area is noted at $y/d = 1$ and $z/d = 1$, which may indicate the vortex position. The oil streak flow patterns suggest vortex flow in this region, and also near $z/d = 5$. It thus appears that the jet has displaced and disrupted the vortex generated by the single tip injector.

In contrast, the pressure contours over the unswept injector (fig. 13(a)) without injection, suggest only parallel flow with no vortex. These contours do not indicate the presence of tip vortices, which may have existed outside of the measurement field. The pressure decreases near the plate suggesting boundary layer and nonisentropic flow losses. With injection (fig. 13(b)) pressure contours over the unswept injector form a concentric ring pattern. As shown in figure 13(a) this injector does not generate a vortex. The concentric ring pitot pressure contours of figure 13(b) must thus be entirely attributed to the jet.

Effect of Injection on Lateral Position of Vortex Core

Pitot and static pressures profiles in the y direction for the sweptback injectors were obtained at $x/d = 0$ (fig. 14). The pitot pressure minima nearest the injector surfaces are assumed to indicate the position of the vortex core in the y direction at $x = 0$ with no injection. At downstream stations the y positions of the vortex cores with no injection are determined from the contours of figures 11(a) and 12(a). The position of the vortex core in the y direction as a function of downstream distance with

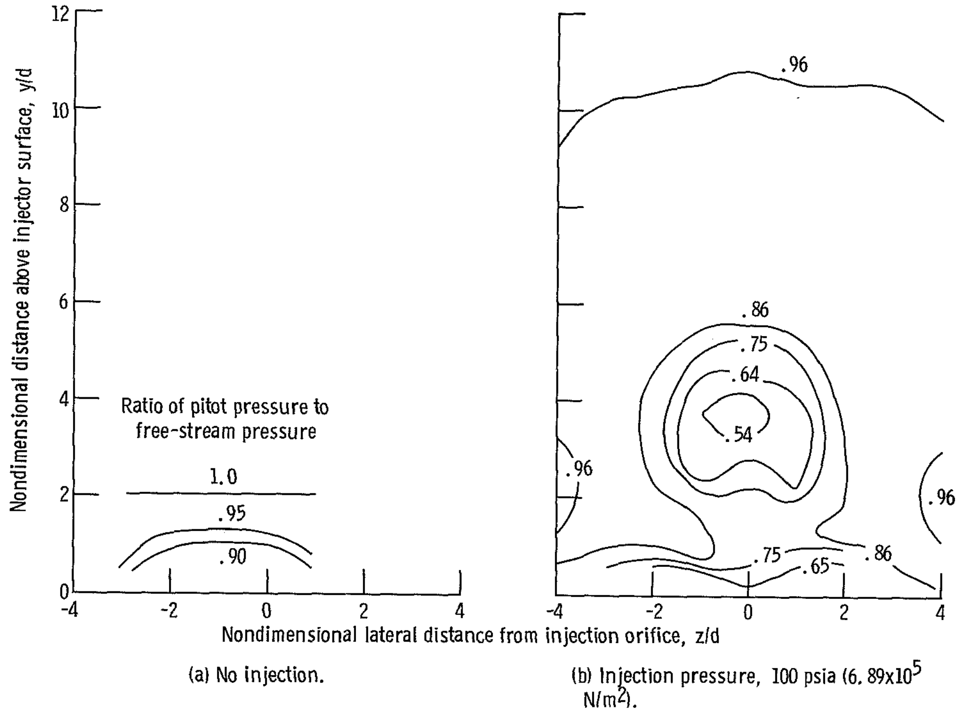


Figure 13. - Pitot pressure contours above unswept injector. Nondimensional downstream distance; 15.2. Viewed from downstream direction.

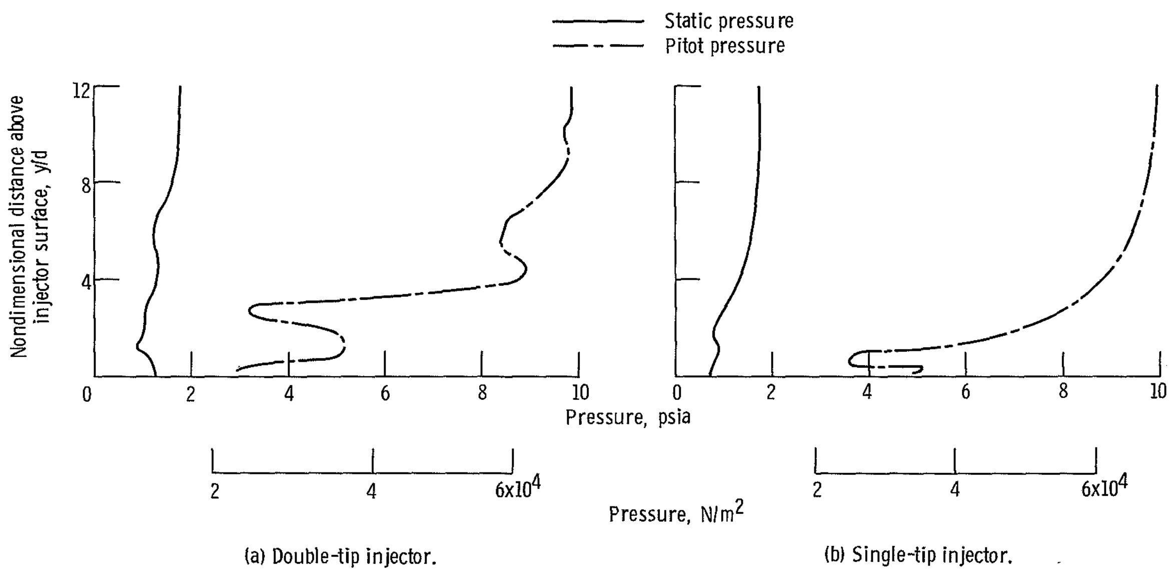


Figure 14. - Pitot and static pressures above injection orifice (x/d = 0) for double- and single-tip injectors.

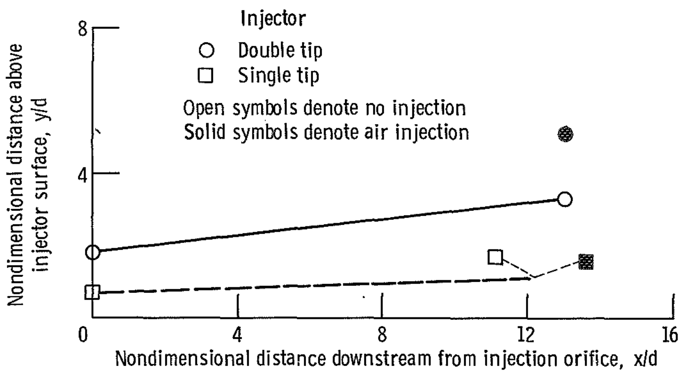


Figure 15. - Effect of injection on vortex core position above plate surface.

no injection is thus established, as shown in figure 15. These results show that the core of the vortex generated by the double tip is further from the plate than that of the single-tip injector. Also shown are downstream positions of the vortex core with air injection. These points were determined from the pitot pressure contours of figures 11(b) and 12(b).

The results show that the combined jet and vortex of the double-tip injector is further from the plate surface than the vortex without injection. However, the vortex position in the y direction for the single tip injector is nearly unaffected by the jet. The vortex core position for the single-tip injector with injection for this comparison was assumed to be at the low-pressure region $y/d = 1$ and $z/d = 1$ in figure 12(b).

Comparison of Flow Stream Momentum Over Swept Injectors

It has been shown (as in ref. 4) that jet penetration varies inversely with the square root of free stream momentum ρv^2. It is desirable then to compare the stream momentum over the injector surfaces in the region of injection.

The Rayleight pitot-tube equation was used to calculate the Mach number profile (shown in fig. 16) from the pitot and static-pressure profiles. The free-stream momentum profiles were then calculated from the Mach number and static-pressure profiles, using the expression γPM^2, as shown in reference 6. The resulting ratio of stream momentum over the double tip injector to that over the single tip injector is shown in figure 17.

The momentum ratio of the two streams is a rapidly varying function of distance above the plate surface. Therefore, the average momentum ratio was calculated (as shown in fig. 18). This result shows that the stream momentum averaged from the plate surface to any distance above the surface is always less for the double-tip injec-

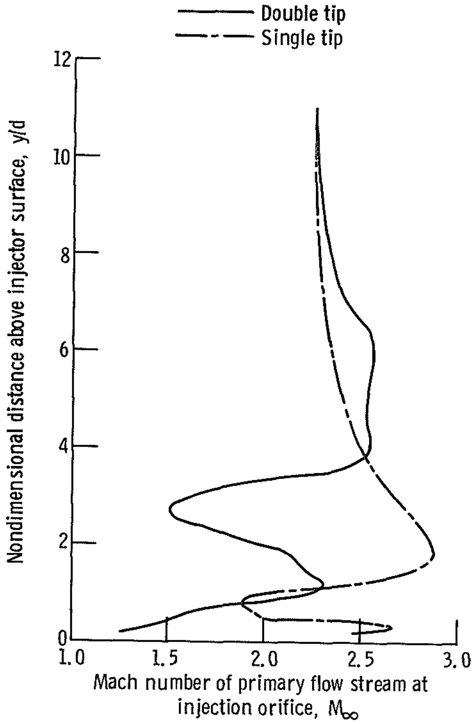


Figure 16. - Mach number (in free-stream direction) over injection hole (x/d = 0) for double- and single-tip injectors.

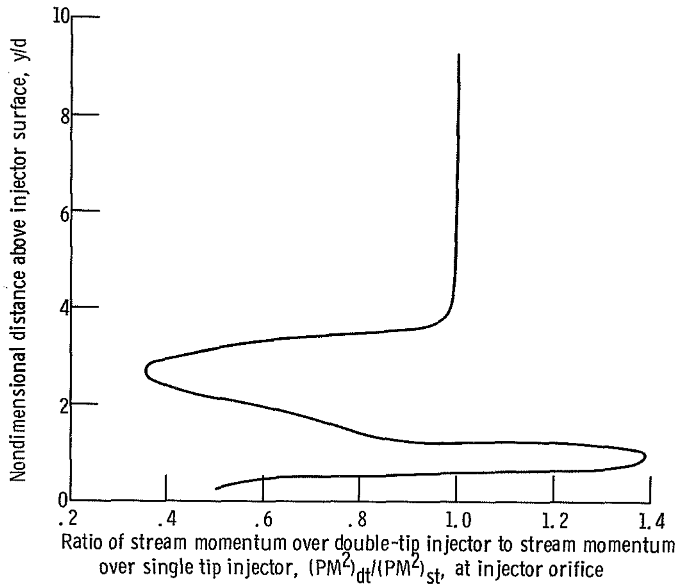


Figure 17. - Comparison of stream momentum over double- and single-tip injector.

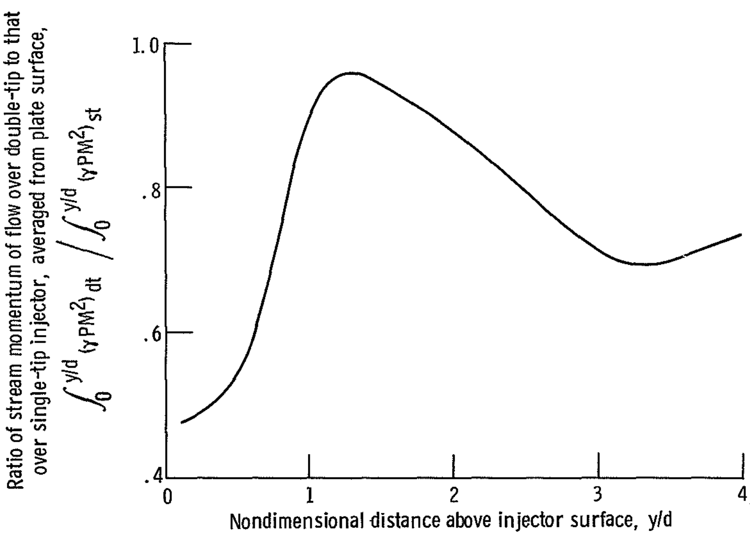


Figure 18. - Averaged momentum ratio of flow stream over injector orifice (double tip to single tip) as function of distance above injector surface.

tor. One effect, then, of the interacting vortices is to lower the stream momentum in the region of injection. The increased penentration observed with the double-tip injector may be partially attributed to the lower momentum over this injector surface relative to that of the single tip injector.

For example, if the upper jet boundary is assumed to be at $y/d = 4$, then the value of the average momentum ratio from $y/d = 0$ to $y/d = 4$ is 0.73. Since penetration has been shown to be inversely proportional to the square root of free-stream momentum, then

$$\frac{\left(\frac{y}{d}\right)_{dt}}{\left(\frac{y}{d}\right)_{st}} \propto \left[\frac{(PM^2)_{st}}{(PM^2)_{dt}}\right]^{1/2} = 1.17$$

This calculated increase in penetration (17 percent) is in excellent agreement with that observed experimentally (see fig. 7).

Relevance to Supersonic Combustors

The experimental data of this study suggest that the double-tip injector might be considered a practical injection concept for a supersonic ramjet combustor. Results obtained here indicate that fuel penetration and spreading are improved with this configuration. However, total pressure losses due to both the jet and injection device must also be considered. These losses must be offset by increased combustor performance. Although the losses were not measured here, the near field penetration results would seem to warrant further investigation of the interacting vortex concept for application to supersonic combustion injection.

CONCLUDING REMARKS

Measurements were made of jet penetration into converging counter-rotating vortices in a Mach 2 airstream. Results were compared with injection into a single vortex and injection into a vortex free flow field. The counter-rotating vortices were generated by a double-tipped injector having two opposing sweptback leading edges. The single vortex was generated by an injector with one sweptback edge. Injection into a vortex free flow field was from a flat unswept plate. The injectors were all at a 6° angle of attack. Injection pressure was varied from 60 to 100 psia (4.14×10^{5} to

6.89×10^5 N/m^2) at sonic velocity. Measurements were made from 0 to 15 jet diameters downstream from the injection orifice and over a lateral range of about 8 jet diameters. The following are concluded:

Increased penetration was always observed with the interacting vortex injector. At 12 jet diameters downstream from the injection point, penetration for this injector was 11 to 18.5 percent greater than for the single vortex injector. In addition, the jet and counter-rotating vortices shed by the double-tip injector combined to form a single flow system. The jet was completely separated from the plate surface at about 13 jet diameters downstream from the point of injection.

In contrast, the jet and vortex shed by the single-tip injector did not combine, but appeared to retain their separate identities. Furthermore, the jet appeared to displace and disrupt the vortex shed by this injector. Also, a portion of the jet remained attached to the single tip injector surface, thereby reducing penetration.

It was found that the momentum of the flow stream in the injection region was lower for the double tip than for the single-tip injector. Flow spillage over the crotch of the double-tip injector into the leeward flow field was considered, but appeared to be small. Therefore, it is concluded that the flow phenomena associated with the counter rotating vortices lowered the momentum in the region of injection which also aided the jet penetration attained with the double tip injector.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 30, 1970,
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